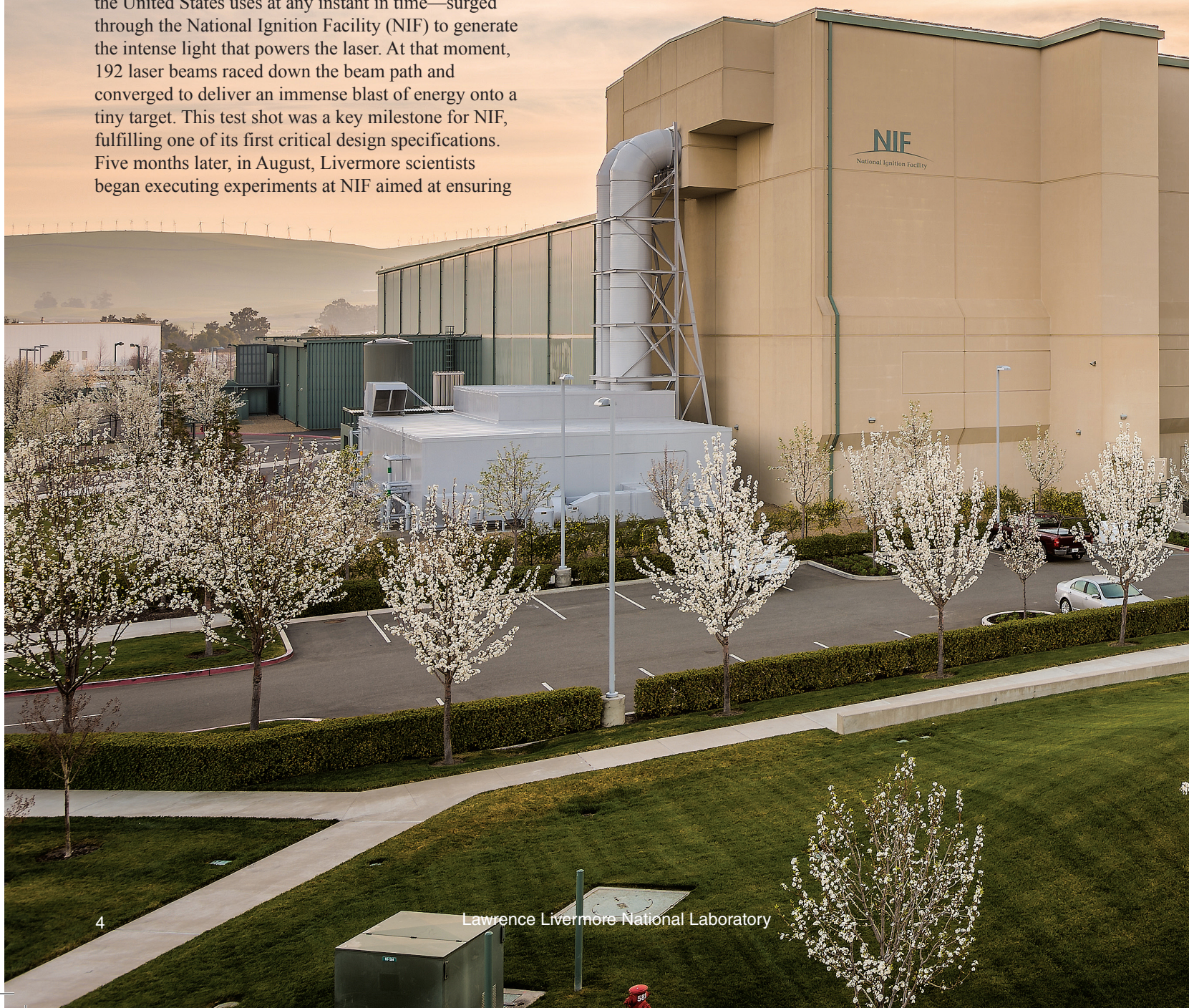


NATIONAL IGNITION CELEBRATES 10 YE

Over the last decade, the world's most energetic laser has been making important contributi

ON March 9, 2009, a staggering 2 trillion watts of electrical power—4 times more power than the United States uses at any instant in time—surged through the National Ignition Facility (NIF) to generate the intense light that powers the laser. At that moment, 192 laser beams raced down the beam path and converged to deliver an immense blast of energy onto a tiny target. This test shot was a key milestone for NIF, fulfilling one of its first critical design specifications. Five months later, in August, Livermore scientists began executing experiments at NIF aimed at ensuring

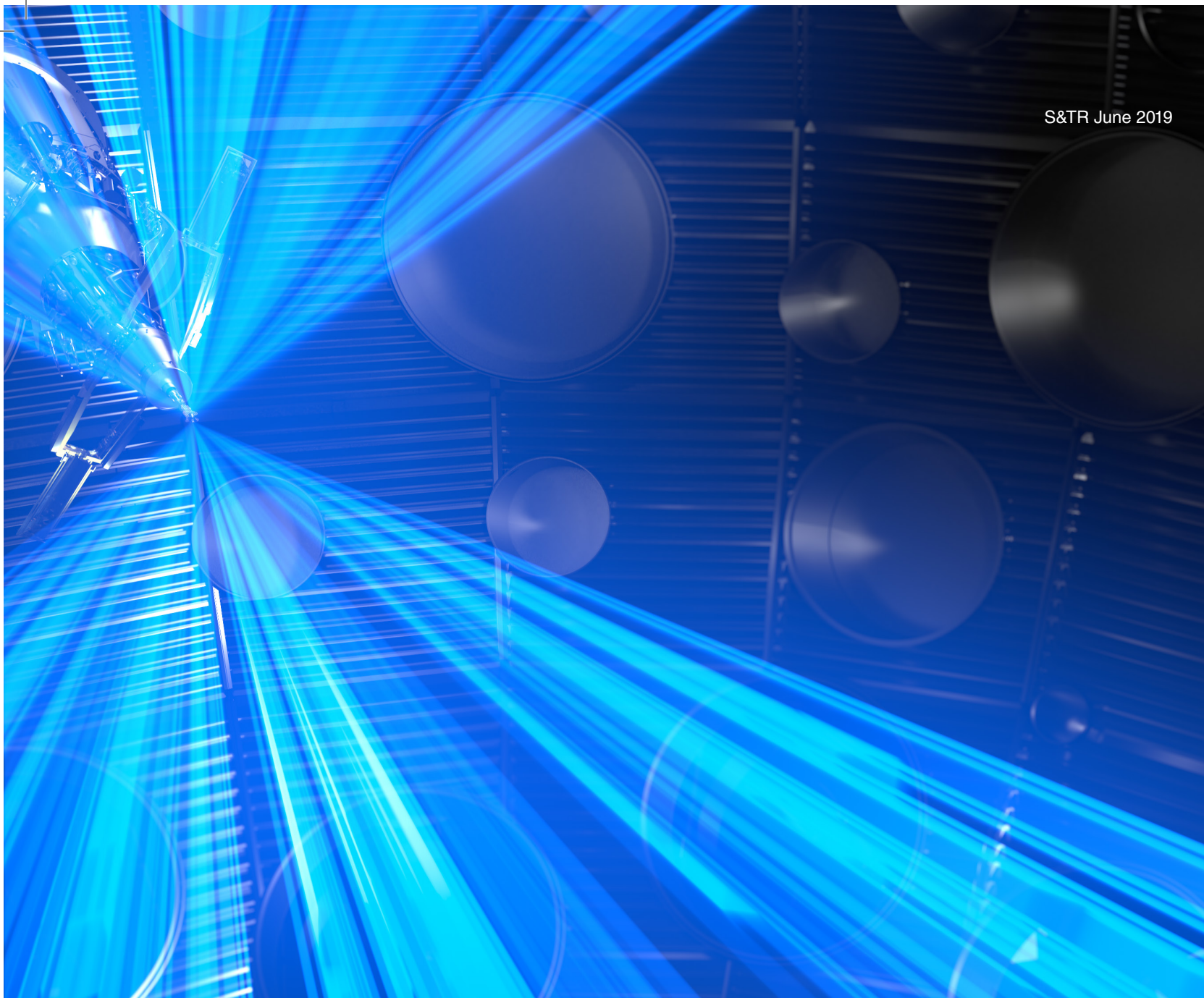


FACILITY ARTS OF OPERATION

ons to the Stockpile Stewardship Program, national security, and high-energy-density science.



The size of three football fields, the National Ignition Facility (NIF) is the most energetic laser in the world—offering unparalleled laser performance and precision for critical scientific applications. (Photo by Damien Jemison.)



Inside NIF, 192 high-energy laser beams converge onto a tiny target to create extreme conditions. (Rendering by Jacob Long.)

the Laboratory could deliver on one of its key missions: to maintain the nation's nuclear deterrent in the absence of further underground nuclear weapons testing.

This exceptional laser system makes it possible for scientists to explore physical regimes never before seen in a laboratory setting. Every year, researchers conduct experiments at NIF that are essential to the National Nuclear

Security Administration's (NNSA's) Stockpile Stewardship Program (SSP). In doing so, they advance our national security and the field of high-energy-density (HED) science. They also enable advances in astrophysics, planetary physics, hydrodynamics, and materials science. NIF's unique capabilities include flexible and repeatable experimental configurations, precision target fabrication and metrology, and advanced diagnostics. Such capabilities enable stockpile stewards from all three NNSA laboratories to execute experiments that deliver data in relevant regimes

previously inaccessible to SSP. Weapons researchers are now able to measure the phase, strength, and equation of state of plutonium and other weapons-relevant materials at extreme pressures, densities, and temperatures. The data from those experiments are used to validate three-dimensional weapons simulation codes and inform life-extension programs (LEPs), the regularly planned refurbishments of nuclear weapons systems to ensure long-term reliability.

Much of NIF's success can be attributed to the Livermore scientists and engineers who have driven significant enhancements

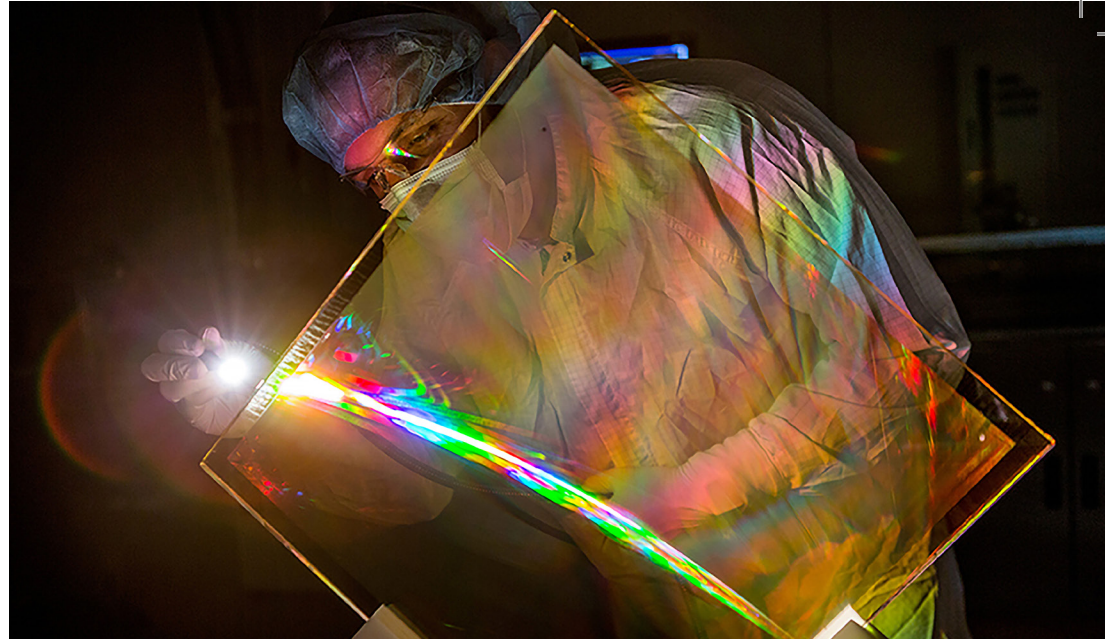
to NIF operations and experimental capabilities over the last 10 years. Their accomplishments have made the facility more efficient while expanding the depth and breadth of scientific applications. Such innovation has led to outstanding contributions in HED science and groundbreaking experiments in many of the Laboratory's mission areas.

NIF's chief engineer Doug Larson says, "We're constantly improving the capability of the laser from the standpoints of how much energy and power we can generate, the precision with which we can deliver it, and how we can diagnose the experimental output. We also continually engineer improvements to operational efficiency, identifying anything that will make NIF more productive for the Stockpile Stewardship Program." An ever-expanding list of target and diagnostic platforms in addition to continued efficiency gains sets the stage for NIF to continue to advance the Laboratory's missions further into the 21st century.

From Concept to Reality

As early as the 1970s, scientists at Livermore began to explore using powerful lasers to achieve ignition of a self-sustaining nuclear fusion reaction. Toward this end, the original NIF concept called for a larger, more complex laser named the Laboratory Microfusion Facility (LMF) that could deliver 10 megajoules (MJ) to a target. Based on data from Livermore's earlier laser systems and other experiments, 10 MJ would be sufficient to exceed the ignition threshold and to achieve higher efficiency and high gain—where more energy is produced from the reaction than the amount of energy used to initiate it.

When asked by the U.S. Congress to evaluate the feasibility of LMF, the National Academy of Sciences recognized the merit and importance of the endeavor and, in 1989, endorsed an ambitious plan to move forward, but with a substantial change. "According to the academy, LMF would probably work,



Laser-induced damage to the thousands of optics within NIF can limit the system's performance. Here, Livermore processing engineer Marcus Monticelli inspects the antireflective coating on a NIF grating debris shield. The coating helps reduce optics damage and improve laser performance. (Photo by Jason Laurea.)

but it viewed 10 MJ as a step too far," recalls John Lindl, NIF's chief scientist during its development. "It would cost too much and be too big an advance in technology. Instead, we were asked to consider something in the 1- to 2-MJ range, which would be closer to the onset of ignition. This revised concept became NIF." Extensive planning followed to determine the facility's design and performance specifications, and in 1996,

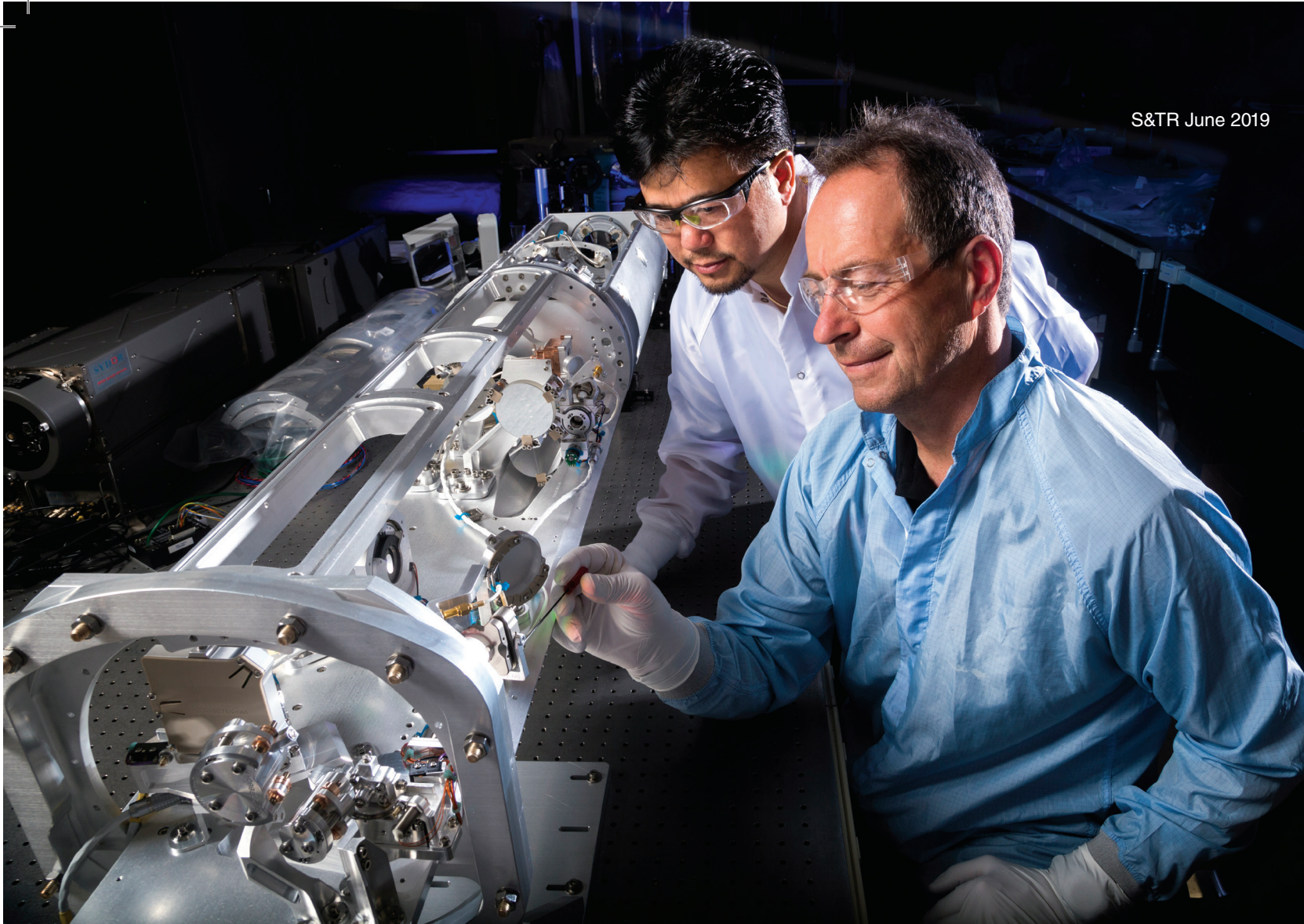


In June 1999, after careful preparation, a rotating crane hoisted NIF's target chamber and gently moved it to the facility's target bay, a breathtaking event that took only about 30 minutes to complete.

authorization was given to proceed with full construction.

Scientists, engineers, and technicians encountered and overcame daunting technical challenges to realize NIF, from developing one of the world's most sophisticated computer control systems to perfecting rapid-growth processes for the large single crystals of potassium dihydrogen phosphate (KDP) and deuterated KDP used in NIF optics. (See *S&TR*, September 2002, pp. 20–29.) One of the most important innovations was developing a means for limiting and repairing damage to optics sustained from repeated exposure to the laser's high-energy beams.

Laser and system engineer Mary Spaeth joined the team to address the threat of optical damage greatly hindering NIF's performance. "NIF's specification was 1.8 megajoules and 500 terawatts. If we'd have come up with only a fraction of that output, we'd be nowhere close to our goal," says Spaeth. Rethinking the science behind the issue, Spaeth was able to lay the groundwork for the optics-recycling loop now in place at NIF. This process offers a novel way to evaluate, refurbish, replace, and reintroduce optics, as needed.



An extensive suite of diagnostics is required at NIF to accommodate its diverse experiments. Shown here, engineering technical associates Gene Frieders (front) and Gene Vergel de Dios work on the optical Thomson scattering diagnostic for recording time-resolved spectra from experiments. (Photo by Randy Wong.)

In 2018, the NIF laser system set a new facility record, firing 2.15 MJ to its target chamber—a more than 15 percent improvement over NIF’s design specification. The achievement is the result of sustained science and technology investment in NIF to realize a fundamental understanding of optical damage and develop the processes to overcome it. “By reaching higher energies, we can enhance the science NIF delivers in support of the Stockpile Stewardship Program,”

says NIF director Mark Herrmann. “This demonstration serves as the first step on a path that could allow NIF to operate at substantially higher energies than ever envisioned during NIF’s design.”

NIF Continues to Evolve

Livermore staff has greatly increased NIF’s operational efficiency by building on their knowledge of the laser system and the complex interplay of targets, positioners, and diagnostics within the target chamber. Early on, the NIF team had to perform lengthy verification procedures before a single experiment could be executed. This process was needed to ensure the experiment would yield useful data and that it would not result in or lead to subsequent damage to the system. Over time, upgrades such as automation of time-consuming manual activities, an advanced laser

alignment system, an integrated suite of online tools, and methods for gleaning more data from a shot, have steadily increased the rate of data generation at NIF.

Between 2014 and 2016, the NIF team achieved more than a 100 percent increase in the number of experiments through efficiency improvements. As an example, the team instituted “mini-campaigns,” wherein similarly configured experiments are grouped together to minimize changes between shots. (See *S&TR*, March 2015, pp. 20–22.) Workflow tools were also developed to guide teams throughout an experiment, from proposal submission and project reviews to scheduling and data analysis. In recent years, NIF has conducted about 400 shots per annum. Notably, in 2017, NIF celebrated its 2,000th shot. Additional improvements, such as the Advanced Tracking Laser

Alignment System (see *S&TR*, March 2017, pp. 16–19) and the Target Alignment Sensor now work together to streamline the alignment of diagnostic instrument manipulators with the target, further increasing shot accuracy and repeatability.

Development of advanced diagnostic capabilities is required for measuring and characterizing a broad spectrum of experiments. Experimenters rely on an array of nuclear, optical, and x-ray diagnostic instruments to record vital data from NIF shots at micrometer and picosecond (trillionth of a second) scales. (See *S&TR*, April/May 2018, pp. 21–23; December 2010, pp. 12–18.) More than 90 diagnostic systems are available to experimenters, and researchers develop roughly a dozen target diagnostics each year to support needed measurements. One key addition to the NIF suite of tools is the petawatt-class Advanced Radiographic Capability (ARC) laser, commissioned in December 2015. (See *S&TR*, September 2018, pp. 4–11.) ARC's main purpose is to diagnose complex hydrodynamic experiments and improve the quality of inertial confinement fusion (ICF) implosions. It also serves experiments for the Discovery Science Program that investigate fundamental physics, such as matter–antimatter pair creation.

Fusion and Ignition

Over the past decade, ICF experiments at NIF have shown exciting progress and have provided extensive insight into the most viable paths for achieving ignition. As outlined at the beginning of SSP in the 1990s, achieving ignition at NIF is a significant goal, as it will enable the study of important weapons physics issues. In indirect-drive ICF experiments at NIF, a deuterium–tritium (DT) fuel capsule is seated inside a hohlraum, a cylindrically shaped device with open ends. When NIF's laser beams strike the hohlraum walls, a bath of x rays is generated that causes the capsule to implode, heating and

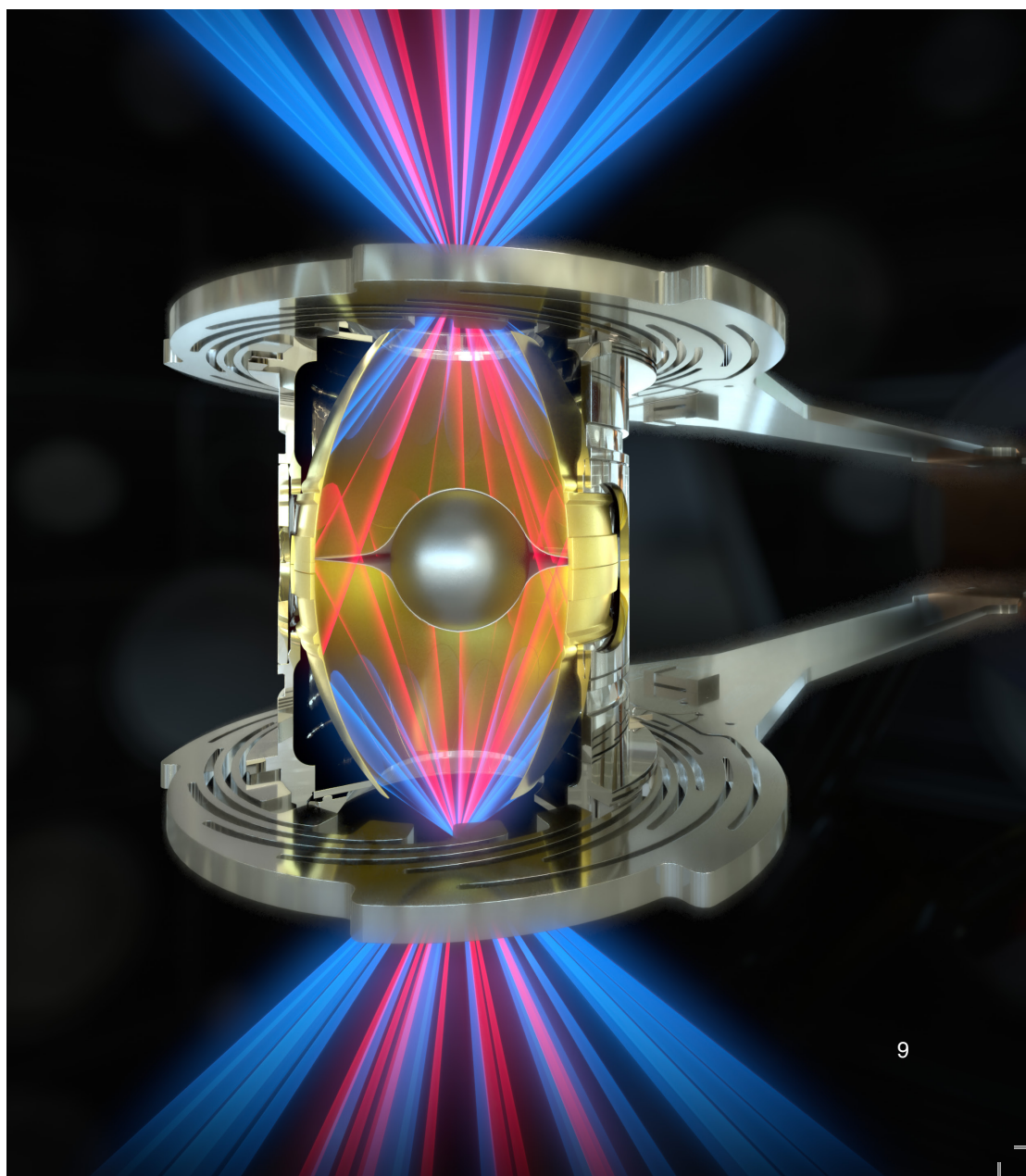
compressing the DT fuel into a central hot spot wherein fusion occurs.

Debbie Callahan, the ICF program associate division leader, worked on a series of experiments—called the High-Foot Campaign—to investigate whether changing the laser pulse shape and making some performance concessions would reduce the hydrodynamic instabilities that dampen the fusion reaction in the target capsule. (See *S&TR*, June 2014, pp. 4–10.) Callahan says, “Ignition is a hard, complex problem. If we make one change, that adjustment can affect other aspects of the experiment, for better or for worse.” In this case, the tradeoff was worth it, as Livermore scientists demonstrated fuel

energy gain—more thermonuclear yield than energy delivered to the compressed fuel by the laser—a major milestone on the path to ignition.

Livermore researchers have been systematically exploring how to maximize the amount of energy that reaches the fuel capsule and implodes the fuel symmetrically to achieve higher fusion yields. Options are under study

Rugby hohlraums are wide at the center and tapered toward the ends like a rugby ball. This shape is one of several under development for improving the energy efficiency and symmetry of inertial confinement fusion implosions. (Rendering by Jacob Long.)



to improve the design of both the fuel capsule and the hohlraum.

Hohlraums are typically filled with helium gas to help slow the expansion of plasma from the cylinder's walls that interferes with the propagation of the laser beams. However, a high gas concentration increases laser-plasma instabilities (LPI). Thus, some new hohlraum designs feature a much lower helium gas concentration, while others include a specialized foam liner on the hohlraum's inner walls, reducing LPI and increasing the conversion efficiency from the laser energy to x rays. Livermore scientists found that

changing the target capsule material to high-density carbon, rather than plastic or beryllium, enabled the most efficient use of the low-gas-density-filled hohlraum while maintaining good implosion symmetry—a key factor for ignition. Reduced radiation loss from the hot compressed fuel, as well as some improvement in symmetry, was also realized by reducing the size of the microscopic fill tube used to transfer the fuel into the capsule from 10 to 5 micrometers in diameter. (See *S&TR*, March 2018, pp. 16–19; January/February 2016, pp. 4–11.)

To provide better control of the plasma or to accommodate a larger fuel capsule, changes to the hohlraum's shape are being explored, such as the rugby hohlraum. This hohlraum shape, which is wide at the center and tapered toward the ends like a rugby ball, may allow for a capsule with a radius about 50 percent larger than usual, exposing more surface area to capture energy.

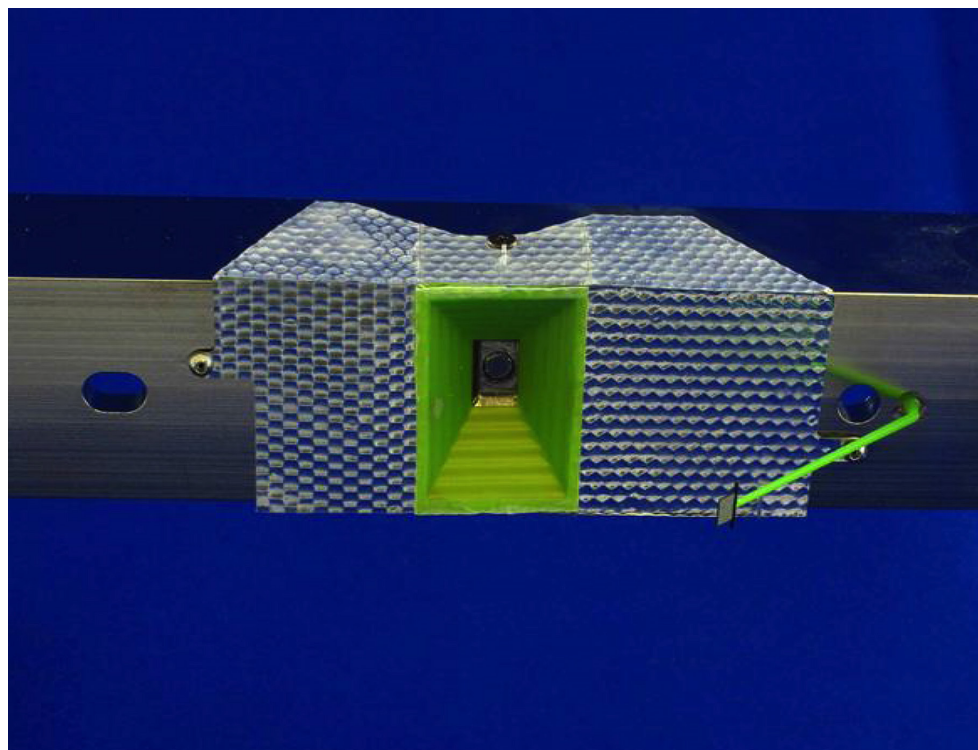
Supporting Our Nuclear Deterrent

All NIF experiments serve SSP, which ensures the safety, security, and effectiveness of the nation's aging nuclear stockpile in the absence of underground testing, by advancing knowledge of HED physics. NIF makes it possible for Livermore scientists to acquire stockpile-relevant data at greater pressures and temperatures than other facilities. The information gathered from NIF experiments also helps improve and validate physics models in simulation codes. Physicist Alan Wan, who leads the Weapons and Complex Integration Principal Directorate's HED weapons-science effort, explains, "HED physics experiments help to assess, design, and provide confidence in the nation's nuclear stockpile today and prepare for the challenges that our country will face in the future."

Information from NIF experiments, combined with existing underground test data and validated computer simulations, are used to make judgments on the stockpile. HED experiments have helped scientists identify important material behaviors and properties that improved understanding of complex phenomena. As an example, NIF experiments contributed to resolving a long-standing issue with energy balance that had plagued weapons physicists for more than 40 years. (See *S&TR*, July/August 2015, pp. 6–14.) A second major success relates to NNSA's complex-wide program to study plutonium under stockpile-relevant, high-pressure conditions. Over more than 4 years, NIF has safely executed 18 experiments for this program.

NIF also supports Livermore's LEPs, which aim to prolong the service life of various nuclear weapons systems. As part of an LEP effort, NIF scientists were tasked with evaluating the efficacy of a material to replace a legacy material whose manufacture posed significant environmental and safety considerations. By adapting an existing HED platform, the NIF scientists successfully assessed the material on an accelerated

The TARDIS (Target Diffraction In-Situ) diagnostic package has a tantalum and tungsten target body, which houses the material sample; an x-ray source target mounted on a stalk; and a semicircular diagnostic cartridge containing image plates to capture the sample's x-ray diffraction pattern.



timeline—2 years, instead of the typical 5 to 10 years. Wan says, “The HED program has proved its worth in delivering for SSP.”

A Universe Brought to Earth

NIF promotes a robust Discovery Science Program in addition to its core national security portfolio. Physicist Bruce Remington, who leads the program, adds, “NIF offers 8 percent facility time, or roughly 18 days per year, to researchers at the Laboratory, in the United States, and abroad to propose open, basic science experiments. The proposals are judged on scientific merit and how well they fit with NIF’s capabilities.” (See *S&TR*, January/February 2012, pp. 4–11.)

Remington’s program receives between 20 and 40 proposals a year, of which roughly 65 percent come from outside the Laboratory. Principal investigators for selected proposals (about a quarter of the time requested) are paired with Livermore personnel, who help them design and conduct successful experiments. Over the years, experiments have delved into a range of fundamental scientific areas, including nuclear reactions under HED conditions; the interiors of planets, stars, and supernovas; and relativistic antimatter–matter plasma energy bursts from black holes. (See *S&TR*, April/May 2016, pp. 12–14.)

Remington views NIF’s Discovery Science Program as much more than a way to conduct cutting-edge research. He says, “We attract highly regarded scientists outside of Livermore to engage with us, which keeps a steady flow of new ideas and approaches coming into NIF and helps us establish connections to leading institutions around the world. When we open up the laser to other scientific endeavors, we find ourselves conducting research that is interesting scientifically and overall beneficial—directly or indirectly—to NIF’s other core missions.”

One such example is the target diffraction in-situ (TARDIS) diagnostic, which was developed to investigate the phase changes between states of matter

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that occur in materials under pressures and temperatures comparable to those believed to exist in the cores of “super-Earth” extrasolar planets (those that are 3 to 20 times more massive than Earth). Researchers have used TARDIS to quantify the changes in materials’ crystal structures as a function of applied pressure, providing clues to planet formation as well as to the exotic behavior of materials at high densities. Refinements made to TARDIS during discovery science experiments have made the platform applicable to its newest use—examining the properties of critical materials for SSP needs.

Lighting the Path

Years of dedicated planning, problem-solving, and innovation resulted in NIF delivering the requested capabilities from the start. “The first time we fired all 192 beams at 1 megajoule, the whole system worked,” says operations manager Bruno Van Wonterghem, who also led development of NIF’s prototype beamline during the preconstruction phase. “We achieved 1.1 megajoules and had good beam quality. The success was an incredible testament to the design, systems engineering, and overall effort.”

Looking back over NIF’s accomplishments to date, great advances

have been made in the areas of target fabrication, optics, and diagnostics, enabling more frequent, varied, and complex experiments to be performed and greater amounts of high-precision data to be collected. The future of NIF includes additional enhancements that will bring increased laser power and diagnostic capabilities, keeping the facility at the forefront of laser science. Jeff Wisoff, principal associate director for the NIF and Photon Science Principal Directorate, is quick to acknowledge the people who make such breakthroughs in capabilities possible. He says, “NIF fundamentally depends upon the talent and skill of a small army of scientists, engineers, technicians, and many other types of support staff from all across the Laboratory and other institutions to address and adapt to current and future challenges.”

Other countries are recognizing the scientific and national security payoff that a NIF-sized facility delivers. Large laser facilities designed to challenge NIF’s capabilities are being built in other countries, including France, China, and Russia. Their collective goal is similar to NIF’s: to understand matter at high-energy densities and obtain fusion ignition. “We must maintain our lead,” says Wisoff. “Our plan is to continue to provide NIF with greater capability through investments that give experimenters more precision, more energy, and more power so that we can continue to reach our mission goals in the coming years.”

—Dan Linehan

Key Words: diagnostic, Discovery Science Program, high-energy-density (HED) science, hohlraum, ignition, inertial confinement fusion (ICF), laser, megajoule (MJ), National Ignition Facility (NIF), nuclear fusion, Stockpile Stewardship Program (SSP), target, target diffraction in-situ (TARDIS) diagnostic, terawatt.

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